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MORPHOLOGY OF RIFFLE–POOL SEQUENCES IN THE RIVER SEVERN, ENGLAND

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ABSTRACT

Despite the occurrence of riffle–pool sequences in many rivers there are few data concerning riffle–pool unit morphology. Of many criteria proposed to identify riffle–pool units, only three methods can be regarded as objective and robust. These are the 'zero-crossing', the 'spectral analysis' and the 'control-point' methods. In this paper statistics are developed using the first two of these methods to describe the streamwise morphology of 275 riffles and 285 pools which form a continuous 32·1 km reach of the bed of the River Severn in Shropshire, England.

Yalin's theoretical relationship between the average riffle:pool unit length (λ_p) and channel width ($\overline{W}$), $\lambda_p = 3\overline{W}$, applies to the River Severn. Reach-average riffle height ($\overline{H}$) is a constant proportion of bankfull depth ($\overline{h}$); typically $\overline{H} \cong 0{\cdot}16\overline{h}$. Riffle height is a positive function of riffle length. Pool depth is a positive function of pool length. However, both riffle length and pool length increase more rapidly than the bed-level amplitude, such that long riffles or pools are relatively 'flat'. As channel gradient reduces, bedforms flatten and become more asymmetric as riffle stoss sides and the proximal slope of pools lengthen at the expense of riffle lee sides and pool distal slopes. The statistical relationships between riffle steepness (*H/L*) and water depth are similar to those for equilibrium subaqueous dunes.

The Severn data are consistent with Yalin's theoretical analysis relating riffle bedform length (L_r) to water depth, i.e. $L_r = \alpha 2\pi\, h$, wherein $\alpha \cong 1$ for steep near-equilibrium bedforms but $\alpha \cong 2$ to 3 as the relative depth decreases and riffles become long, low features. Theoretical consideration and turbulence data indicate that the frequency of coherent turbulent-flow structures associated with the riffle–pool mixing length in the Severn should be of the order of 50 to 100 s. The morphological similarity of the steepest River Severn riffles with dunes raises intriguing questions with respect to self-similar, convergent organization of periodic alluvial bedforms and to bedform dynamic classification particularly.

KEY WORDS: gravel-bedforms; riffles; pools; riffle–spacings; zero-crossing analysis; spectral analysis; River Severn, UK

INTRODUCTION

Series of bathymetric highs and lows, forming riffles and intervening pools, are characteristic macroscale bedforms in many single-channel alluvial rivers. It follows that a fundamental understanding of riffle–pool dynamics is important for modelling hydraulic adjustment of fluvial morphology. However, a review of the literature produces four signal observations. Firstly, theoretical considerations indicate average spacings of riffle crests (λ_p) can range typically between three and six times the average channel width ($\overline{W}$). Secondly, field data show a wider spread but emphasis usually is given to data which support the function $\lambda_p \cong 6\overline{W}$ (e.g. Hey and Thorne, 1986). Thirdly, despite the importance of correctly identifying riffle–pool sequences, the majority of field studies either specify identification criteria poorly, or utilize criteria that are not robust. Finally, in contrast to qualitative descriptions, there is a dearth of data concerning riffle–pool morphology. In this paper, field data from the River Severn in England are analysed using three robust objective methods. Summary morphological indices are reported and compared where appropriate with theory.

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PERSPECTIVE

The classic works of Leopold and Wolman (1960) and Leopold *et al.* (1964) considered riffle and pool sequences that form within series of river meanders. Leopold and Wolman (1960) argued that meander chord wavelength (λ_m) was a constant empirical function of channel width (W):

$$\lambda_m = 10 \cdot 9W \tag{1}$$

Equation 1 was advocated by Keller and Melhorn (1978) in a test using data different from those used by Leopold and colleagues. However, using theoretical constructs, Richards (1976) indicated that, for the case of straight-line meander chords, λ_m/W varies from about 10 to 14, averaging 12, which is consistent with constant wavelength for given channel width:

$$\lambda_m = 4\pi W \cong 12W \tag{2}$$

As there are two riffle–pool sequences within each meander wavelength, it follows (Richards, 1978) that the theoretical spacing of riffle crests (λ_p) is equal to:

$$\lambda_p = 2\pi W \cong 6W \tag{3}$$

In contrast, considering a meandering thalweg within an experimental straight channel (where alternate bars develop within the apex of each meander), Fujita and Muramoto (1985) found an initial meander wavelength of $6{\cdot}3W$ stabilized at $7{\cdot}25W$. The empirical results of Fujita and Muramoto were used by Nelson (1990) to support a theoretical calculation of the spacing of the riffles between alternate bars. Nelson (1990) suggested an initial spacing of $5W$ increased in time to an equilibrium value of $7{\cdot}5W$. Thus riffle crest spacings are half the meander spacings which is consistent with Yalin's (1971) theoretical construct whereby the arc wavelength of equilibrium meander sequence developed in a straight channel can be defined as:

$$\lambda_m = 2\pi W \cong 6W \tag{4}$$

such that riffles associated with meanders or alternate bars should be spaced approximately every three channel widths. Yalin (1971, 1977, 1992) speculated that the regular riffle spacing is related to the path length (L_l) of periodic macroturbulent eddies which extend across the full width of the flow. Further he suggested that the appropriate eddy length for these low-frequency flow structures is proportional to the boundary-layer thickness (δ), or water depth (h) such that:

$$L_l/\varepsilon h = 2\pi \tag{5}$$

where ε is a constant.

Richards' theoretical relationship (Equation 2) represents the central tendency of observed data whilst Yalin's theoretical relationship (Equation 4) defines the lower limit of observed data. Thus theories and field observations diverge by a factor of two, which has gone largely unremarked in the literature (cf. Richards, 1976). Opinions vary as to an explanation for this variance, which only in part is owing to whether chords or arcs are used to define the periodicity in channel wavelength. Hey (1976) advanced an explanation based on there being two counter-rotating periodic macroturbulent eddies in a straight channel, rather than Yalin's one, each occupying approximately half the channel width (see Thompson, 1986). As these cells alternately dominate the flow pattern in a downstream direction, Hey argued that the riffle spacing should be twice that proposed by Yalin. Yalin (1977) noted that field data demonstrate that riffle spacings are an inverse function of depth, which concurs with Hey's (1976) analysis, because as flows broaden and shallow, multiple counter-rotating fluid cells develop across the channel width (e.g. Hey and Thorne, 1976; Yalin and da Silva, 1991, 1992; Dalrymple and Rhodes, 1995). Importantly, Keller and Melhorn (1973, 1978) suggested that the riffle–pool sequence is initiated at $\lambda_p \cong 3W$ in relatively straight channels but for meandering channels spacing

approaches an equilibrium of $6W$ such that as sinuosity increases, additional riffle–pool units develop. Consequently spacings of $3W$ can be regarded either as representing nascent non-equilibrium sequences, in accord with the observations of Fujita and Muramoto (1985) and Nelson (1990), or as a minimum equilibrium value in accord with Yalin (1977). It is evident that these various views should be readily reconciled, as the development of multiple flow cells and channel morphology is clearly a reflexive response.

From the above, it might be argued that in an actively meandering river subject to scour and fill there will be constant variation in bed-level adjustment. Bed bathymetry (and flow cell structure) might then be quite variable along a downstream traverse, producing a series of highs and lows of variable amplitude and spacing. Dury (1970) raised the question '.. of whether [such] complex depressions should be regarded as single or as multiple pools..'. It follows that precise definition of a pool and a riffle is critical to the study of riffle–pool sequences and the method utilized may influence the resultant calculated riffle–pool spacing (Richards, 1976; O'Neill and Abrahams, 1984). A review of over 50 scientific articles shows that all but three published definitions are unsatisfactory, being imprecise. The three robust, objective methods are here termed: the *control-point method* (Yang, 1971); the *zero-crossing method* (Dury, 1970; Nordin, 1971; Shen and Cheong, 1977; Sidorchuk, 1996); and *power spectral analysis* (Box and Jenkins, 1976; Bloomfield, 1976).

For reasons noted below, the control-point method could not be used in this study. Nevertheless this objective method is worth noting. Yang (1971) observed that during baseflow, riffle sequences pond a series of pools. By extending a horizontal surface upstream from the low point in each riffle crest until it intersects the bed upstream, pool lengths can be defined objectively. By this definition bathymetric highs that remain submerged at baseflow do not act as control points. However, in the River Severn it was found that a small number of riffles with pronounced amplitude dominated in each reach. The associated backwaters 'drowned out' many prominent topographic highs that exert some control on the local baseflow conditions.

METHODS

A 32·1 km alluvial stretch of the River Severn (Figure 1) between Welshpool and Shrewsbury was surveyed in 1988 using a Furuno Model FE-4200 echo-sounder and associated constant-speed chart recorder mounted on a large inflatable boat. Prior to survey the stretch was separated into three contiguous reaches (A = 9·5 km, B = 10 km, C = 12·6 km) of differing channel gradient and channel width. Subsequent pre-processing demonstrated that the three data series were self-similar in terms of high-frequency components but could not be concatenated for time-series analysis owing to differing low-frequency (>400 m) components in each series. Throughout the total 32 km the channel is devoid of mesoscale bedforms but is deep, providing the opportunity for the river bed to develop macroscale bedforms of pronounced amplitude. Using a constant chart speed when the river current is varying along a downstream traverse would distort the horizontal scale of the bathymetric record. To reduce this effect to a minimum each survey was conducted when the river was at bankfull as surface velocities in the pools and riffles of the River Severn equalize close to bankfull (Carling, 1991). The boat was allowed to drift, but was steered to keep within the maximum current thread which generally follows the thalweg, thus crossing each riffle crest near its lowest point. In this manner continuous chart records of depth variations were recorded over long series of pools and riffles (Figure 2). The chart was marked with an accuracy of ± 1 m whenever the boat passed prominent bankside features shown on the relevant 1:25 000 Ordnance Survey sheet. The purpose was subsequently to correct short sections of the record for variations in the speed of drift downstream. However, subsequent analysis showed errors to be normally distributed, and linear distortion of the echo-sounding traces was generally less than ± 2 per cent of the reach lengths as recorded on the OS map.

Each reach had minimum variation in channel width downstream. Bank top and bank base widths, and bankfull depths at intervals along the three reaches were determined from field survey at low flow and from survey data provided by the former National Rivers Authority. Average bankfull depths were 6·61 m, 3·41 m and 4·5 m for reaches A, B and C respectively. The average channel gradient is *c.* 0·0065 for reach A, $\leq$ 0·0059 for reach B and $\geq$ 0·004 for reach C. Bed deposits primarily are gravel: d_{50} = 4 to 75 mm, fining to 0·63 mm locally (Carling, 1991; Couperthwaite, 1996).

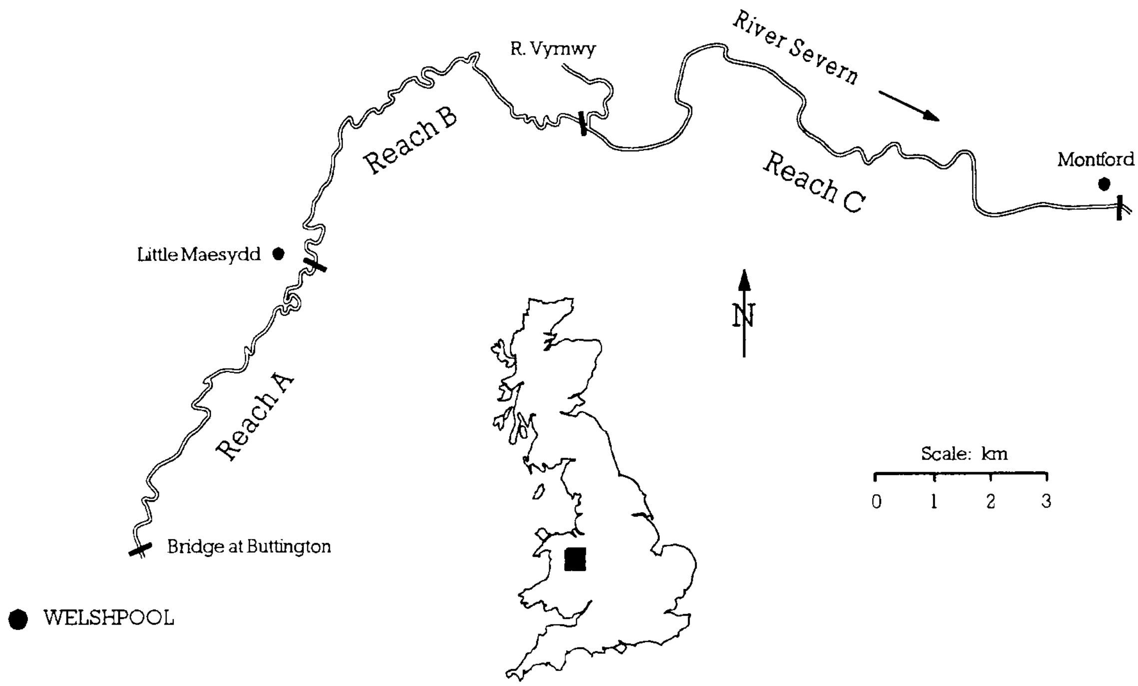


Figure 1. Location of study reaches in the River Severn, UK

Zero-crossing method

The method previously has been applied to river reaches a few hundred metres in length (e.g. Melton, 1962; Nordin, 1971; Church, 1972; Richards, 1976; Milne, 1982) whereas here it is applied to 10 km reaches. O'Neill and Abrahams (1984) criticized the method on two grounds. Firstly, long-period undulations in the long-profile of a river, if not removed prior to data analysis, will result in unrealistic long-wavelength bedforms being identified. Secondly, minor deviations in the bed profile may give rise to isolated, minor residuals of either sign. The first problem is readily addressed by pre-processing the data. In principle, but not in practice (see below), the latter problem can be prevented by consideration of 'tolerance' (O'Neill and Abrahams, 1984) whereby residuals have to be of a given magnitude before they are included in suites of bedform statistics.

Chart records were digitized at 1 mm intervals (equivalent to 10 m on the true horizontal scale), giving a vertical resolution of 70 mm in water depths of 4 m to 8 m. Low-frequency components were removed by applying a low-pass filter to the data to remove spatial features with periodicities longer than 400 m. Positive and negative deviations in the traces were then defined with reference to zero-crossings. The maximum deviations between zero-crossings gave the height (H) or depth (D) respectively of a positive (+) bedform (riffle) or negative (−) bedform (pool) (Figure 3). Similarly the horizontal distances between zero-crossings defined the lengths (L) of individual riffles and pools. No 'tolerance' criterion (O'Neill and Abrahams, 1984) was employed because selection of such a criterion is subjective. We reasoned that if the bed profile is strongly periodic then this would be evident in the central tendency of summary bedform statistics. The asymmetry (L_{r1}/L_{r2}), average angle of riffle stoss sides (A_r) and lee sides (B_r) and the proximal and distal slopes (A_p and B_p) and asymmetry (L_{p1}/L_{p2}) of pools were defined as shown in Figure 3.

Power spectral analysis

Given that bathymetry may exhibit both periodic and random fluctuations, estimates of the frequency (f_o) and the period ($1/f_o$) of characteristic wavelengths may be determined by describing the data as a second-

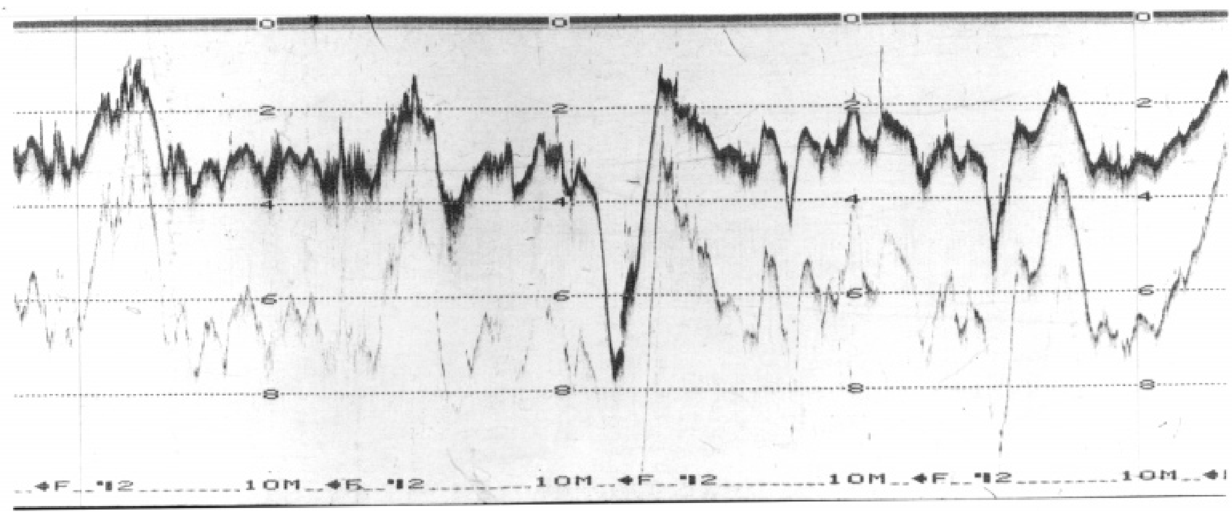


Figure 2. The bathymetry of a 200 m reach of the River Severn showing typical variation in bed elevation. The example is taken from a continuous 10 km trace. Vertical scale is in metres with a zero-origin equal to the bankfull water surface

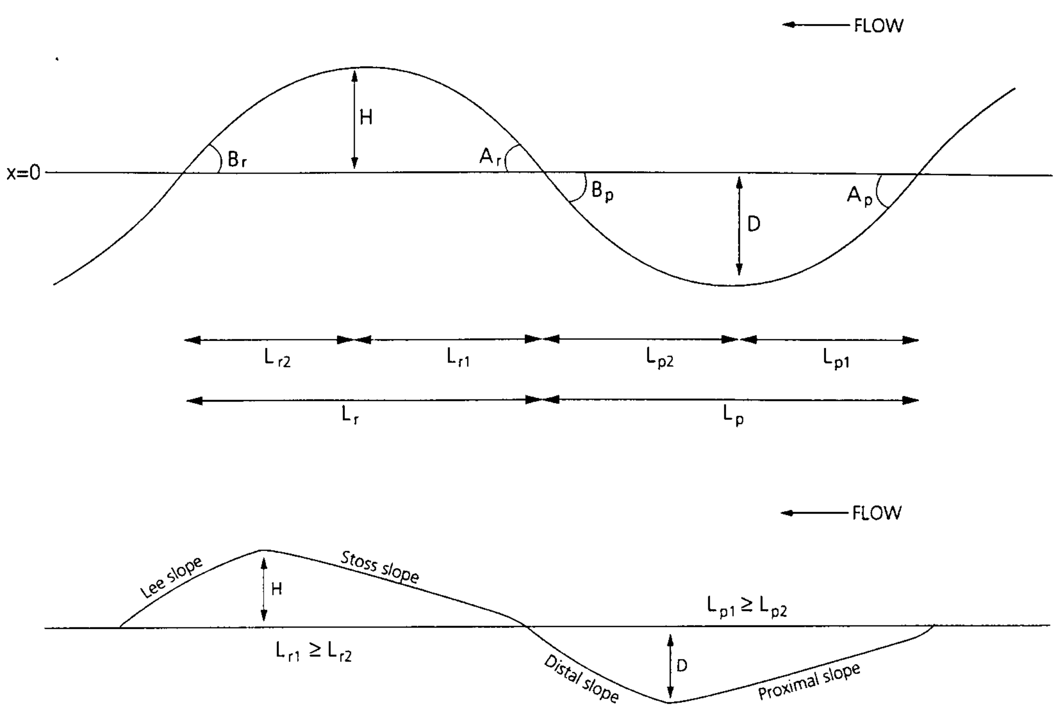


Figure 3. Definition diagram for riffle–pool morphology

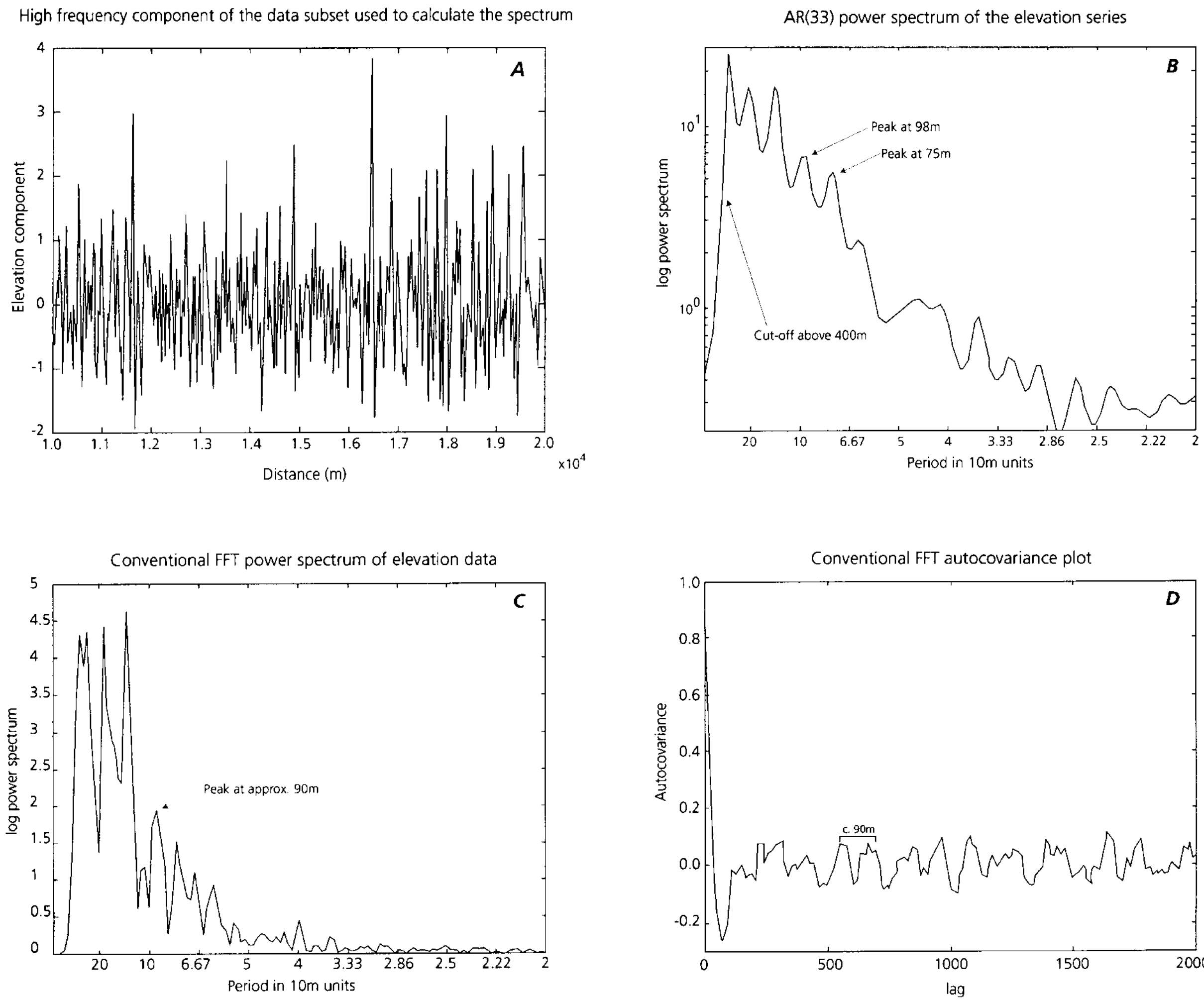


Figure 4. (A) High-frequency component of the data sub-set used to calculate the spectra show in (B) and (C). (B) AR (33) power spectrum for the elevation series in (A). (C) Conventional FFT power spectrum for the elevation series in (A). (D) Autocovariance function for reach B showing an apparent cyclic trend with a wavelength approximating 90 m

order autoregressive process and applying methods of spectral analysis. Applications of spectral analysis to short runs of riffle–pool data have been reported by Nordin (1971) and Richards (1976) amongst others, who noted that spectral density functions and autocovariance functions in particular may define significant periodicity in bed elevation trends.

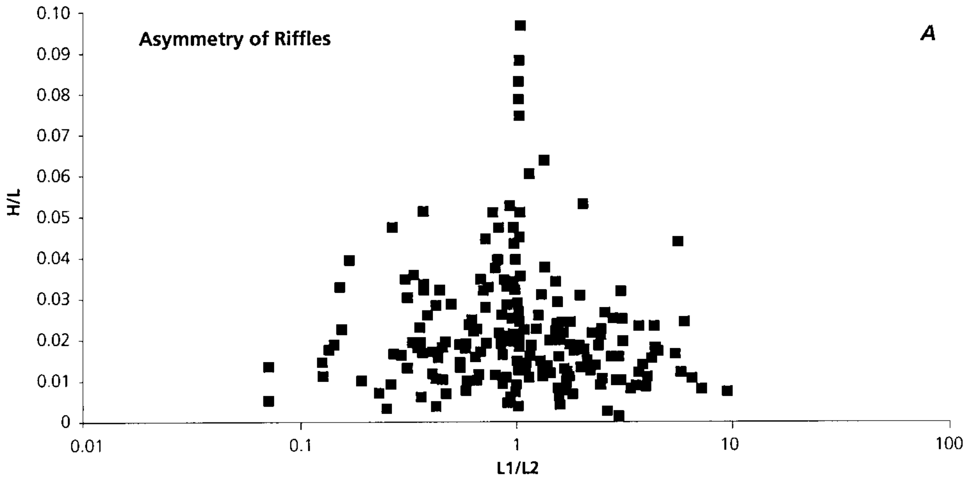
The high-frequency component of a well-defined data sub-set is shown in Figure 4A. This mean stationary series represents the 10 km reach B and has been used to indentify the optimal autoregressive (AR) model order using the Akaike Information Criterion (AIC), which was found to be 33 (Akaike, 1974). The resultant AR model is of the form:

$$y_t = \sum_{j=1}^{p} a_j y_{t-j} + e_t$$

where y_t is the tth sample of the series, a_j is the AR model coefficient for y_{t-j}, the sample lagged by j, and e_t is

Table I. Summary statistics for riffles and pools

	A Riffles								A Pools							
	L	*H*	*H/L*	*L1*	*L2*	*L1/L2*	*A*	*B*	*L*	*D*	*D/L*	*L1*	*L2*	*L1/L2*	*A*	*B*
Mean	47·29	1	0·02	23·07	22·99	1·29	4·54	3·89	43·6	1·08	0·03	22·71	24·87	1·5	5·06	5·18
Standard Error	3·82	0·01	0·002	3·08	2·14	0·17	0·5	0·4	3·91	0·08	0·002	2·19	3·02	0·18	0·44	0·42
Median	36·87	0·75	0·02	16·44	16·62	1	3·02	2·85	34·21	0·95	0·03	17·89	18·01	1	3·76	4·08
Mode	17·53	1·37	0·004	8·7	12·94	1	2 to 3	1 to 3	62·98	0·5 to 0·7	0·02 to 0·03	20·79	3·93	<0·5	3 to 4	3 to 4
Standard Deviation	35·41	0·92	0·02	25·4	17·69	1·42	4·15	3·33	38·75	0·76	0·02	20·06	27·65	1·68	4·04	3·89
Variance	1254·14	0·85	0	645·08	312·82	2·01	17·22	11·08	1501·71	0·57	0·0004	402·55	764·79	2·81	16·35	15·13
Kurtosis	2·42	5·62	3·53	15·01	4·21	15·87	2·96	7	13·67	2·68	3·24	14·33	18·21	10·15	8·93	4·58
Skewness	1·51	2·2	1·91	3·49	1·84	3·59	1·86	2·41	3·15	1·43	1·59	3·23	3·74	3	2·42	1·82
Range	184·23	5·1	0·09	158·36	94·6	9·11	18·39	18·67	262·57	3·92	0·11	135·7	191·61	9·72	26	22·21
Minimum	7·13	0·05	0·004	2·66	2·72	0·13	0·54	0·54	6·41	0·06	0·004	3·2	1·57	0·12	0·41	0·55
Maximum	191·37	5·14	0·1	161·02	97·32	9·24	18·93	19·21	268·98	3·98	0·11	138·9	193·18	9·85	26·4	22·76
Count	86	86	86	68	68	68	68	68	98	98	98	84	84	84	84	84
	B Riffles								B Pools							
	L	*H*	*H/L*	*L1*	*L2*	*A*	*B*	*L1/L2*	*L*	*D*	*D/L*	*L1*	*L2*	*L1/L2*	*A*	*B*
Mean	42·08	0·76	0·03	26·37	29·7	3·15	2·9	1·31	43·35	0·86	0·02	27·01	28·11	1·52	2·91	3·09
Standard Error	4·74	0·05	0·002	2·87	4·94	0·22	0·2	0·11	3·76	0·07	0·001	2·47	3·09	0·15	0·24	0·25
Median	23·97	0·67	0·02	15·24	19·69	2·64	2·49	0·96	31·71	0·68	0·02	20·3	19·73	0·93	2·09	2·23
Mode	11·82	0·14	30 to 40	9·78	8·23	0·6 to 0·9	1·5 to 2·4	.9 to 1·05	18·18	0·17	32 to 40	13·78	12·07	0·3 to 0·6	1 to 2	1·5 to 2
Standard Deviation	52·31	0·51	0·02	26·29	45·24	2·04	1·82	1·03	41·36	0·8	0·02	23·29	29·14	1·43	2·26	2·32
Variance	2736·41	0·26	0·0004	691·32	2046·67	4·16	3·3	1·05	1710·54	0·63	0·0004	542·19	849·15	2·04	5·1	5·38
Kurtosis	18·91	−0·63	10·1	3·69	41·46	−0·02	1·54	1·06	4·79	4·51	25·82	7·59	8·93	2·39	2·71	2·89
Skewness	3·61	0·61	2·67	2·03	5·81	0·82	1·24	1·27	1·98	1·79	3·97	2·37	2·74	1·66	1·71	1·56
Range	396·43	2·06	0·12	117·47	371·24	8·28	8·68	4·19	217·41	4·66	0·16	141·11	166·14	6·24	10·55	11·32
Minimum	4·08	0·07	0·005	3·42	3·18	0·64	0·33	0·07	3·02	0·06	0·005	4·97	3·51	0·2	0·46	0·34
Maximum	400·51	2·13	0·13	120·89	374·42	8·91	9	4·26	220·43	4·72	0·17	146·08	169·64	6·44	11·01	11·66
Count	122	122	122	84	84	84	84	84	121	121	121	89	89	89	89	89
	C Riffles								C Pools							
	L	*H*	*H/L*	*L1*	*L2*	*L1/L2*	*A*	*B*	*L*	*D*	*D/L*	*L1*	*L2*	*A*	*B*	*L1/L2*
Mean	79·74	0·91	0·02	50·21	47·13	1·77	2·25	2·39	88·98	1·13	0·02	54·88	50·43	2·48	2·25	1·86
Standard Error	12·06	0·08	0·001	7·17	9·06	0·22	0·31	0·22	11·09	0·1	0·002	9·21	7·52	0·32	0·21	0·31
Median	39·46	0·73	0·02	27·06	27·58	1·16	1·55	2·11	46·33	0·95	0·01	25·51	25·93	1·68	1·95	1·01
Mode	25·1	0·35	40 to 60	14·15	10 to 15	0·8 to 1	1·4 to 1·6	0·4 to 0·6	18 to 24	.1 to 0·15	20 to 40	22·83	–	0·2 to 0·4	1·2 to 1·6	0 to 0·8
Standard Deviation	98·75	0·64	0·01	52·17	65·94	1·6	2·29	1·62	90·1	0·85	0·02	67·03	54·73	2·3	1·56	2·25
Variance	9751·19	0·41	0·0001	2721·27	4347·53	2·56	5·26	2·62	8117·87	0·72	0·0003	4493·44	2995·91	5·27	2·42	5·08
Kurtosis	8·18	0·77	2·91	2·13	15·02	2·11	6·71	−0·74	4·61	0·06	5·52	12·64	9·14	1·69	1·33	8·31
Skewness	2·57	0·57	1·44	1·67	3·47	1·5	2·47	0·56	1·96	0·82	2	3·12	2·53	1·35	1·1	2·68
Range	555·55	2·24	0·05	203·4	391·51	6·93	11·54	5·87	466·61	3·43	0·09	385·51	304·22	10·16	7·15	11·45
Minimum	4·96	0·04	0·002	4·24	3·82	0·07	0·12	0·25	5·58	0·07	0·002	10·95	8·78	0·21	0·17	0·07
Maximum	560·51	2·28	0·06	207·63	395·33	7	11·67	6·12	472·18	3·49	0·1	396·57	313	10·37	7·32	11·52
Count	67	67	67	53	53	53	53	53	66	66	66	53	53	53	53	53



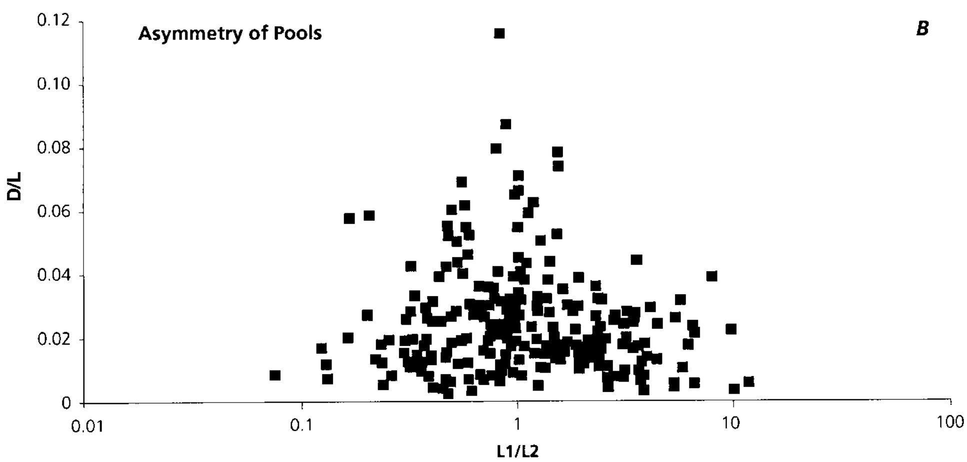


Figure 5. (A) Riffle asymmetry (L_{r1}/L_{r2}) as a function of riffle form index (*H/L*). (B) Pool asymmetry (L_{p1}/L_{p2}) as a function of pool form index (*D/L*)

the white noise. Such autoregressive models are commonly used to calculate the spectral signature of data series where there is no *a priori* reason to suspect a preferred trend. In addition AR models are better for determining the 'persistence' of peak frequency estimates than the more common Fast Fourier Transform (FFT) methods (Marple, 1987). The frequency response is readily calculated from the AR coefficients and is shown in Figure 4B in which the two peaks in the spectrum at 75 and 98 m are flagged. By reanalysing the data for other AR order models the 'persistence' of these peaks was confirmed, in contrast to other frequencies. For example, for AR (26) the peaks are at 80 and 160 m (showing a harmonic relationship) whilst for AR (40) the peaks are at 75 and 95 m. A standard FFT also confirmed the presence of a spectral peak at 90 m (Figure 4C and D), significant within 95 per cent confidence limits as determined by comparison with a second-order red-noise spectrum (Munn, 1970). The persistence of peaks around 90 m, whether using AR or FFT models, confirms the presence of such a frequency, albeit weak, in the elevation series.

RESULTS

Summary data for 275 riffles and 285 pools from the zero-crossing analysis are tabulated in Table I.

Riffle height, length and asymmetry

Riffles rarely exceeded 2 m in height relative to the zero-crossing, with most being less than 1 m high; 0·4 m was typical. Although there was no significant difference in the spread of riffle heights when comparing river reaches, reach-averaged riffle height increased with bankfull water depth, such that mean riffle height is a constant proportion of reach-averaged bankfull depth (see Discussion).

Riffle lengths were strongly positively skewed, with only a few riffles being several hundred metres in length and generally less than 120 m long; the modal length was around 20 m.

Although many riffles are asymmetric with longer stoss sides (L_{r1}) compared to the length of the lee side (L_{r2}), the distributions for each reach are skewed with a tail of large L_{r1}/L_{r2} values. Within reaches A, B and C the modal values are close to 1·0. This demonstrates that many riffles are symmetrical or have stoss slopes shorter than the lee sides (Figure 5A).

The lack of preferred asymmetry means that there is no statistically significant difference in the distributions of stoss and lee side angles (Snedecor's F-test). These angles are usually only a few degrees, generally less than 6° with a few extreme values up to 19° on both stoss and lee sides (Figure 6).

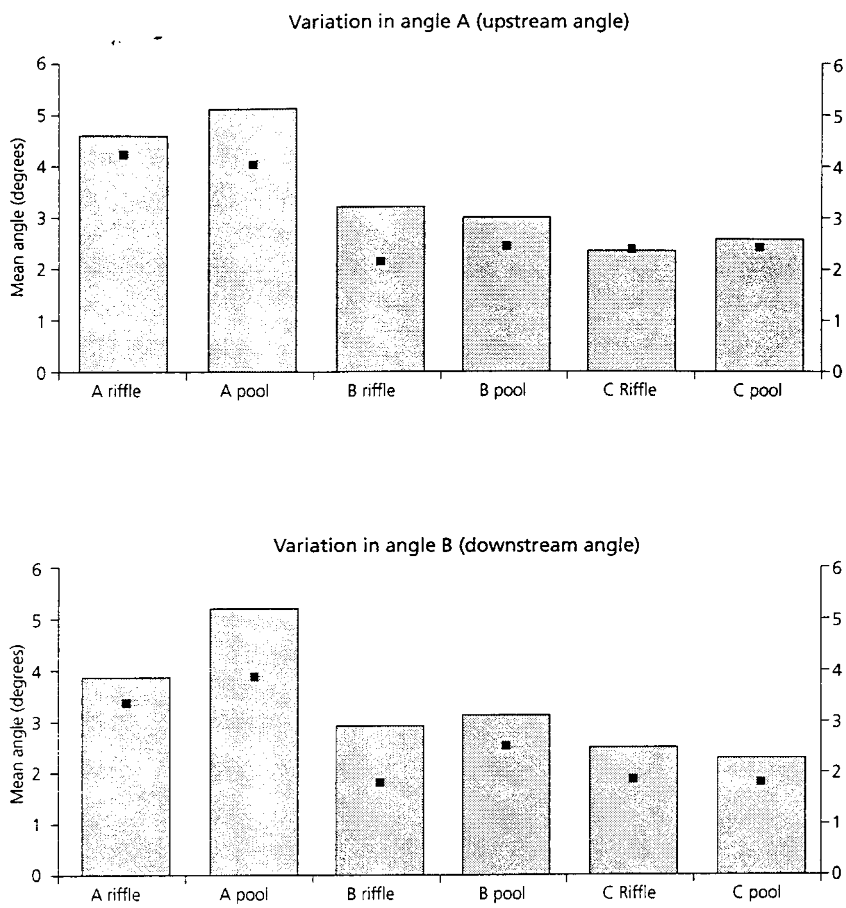


Figure 6. Histograms of summary slope angle data for pools and riffles. Point data are the values of the standard deviations

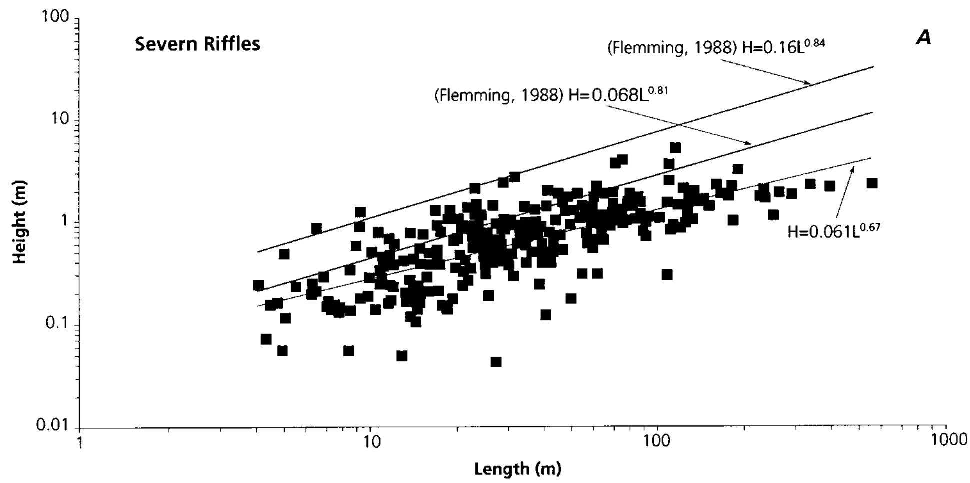
Riffle heights are correlated positively with riffle lengths (Figure 7A). Considering all the 275 data points:

$$H = 0 \cdot 06 L_r^{0 \cdot 666} \qquad r^2 = 0 \cdot 51 \tag{6}$$

or

$$H/L_r = 0 \cdot 06 L_r^{-0 \cdot 333} \tag{7}$$

The exponents of less than 1·0 are as expected. Riffles have to be depth-limited, such that although riffle length may increase, riffle height is constrained by the need to maintain conveyance at bankfull between riffle crest and the banktop.



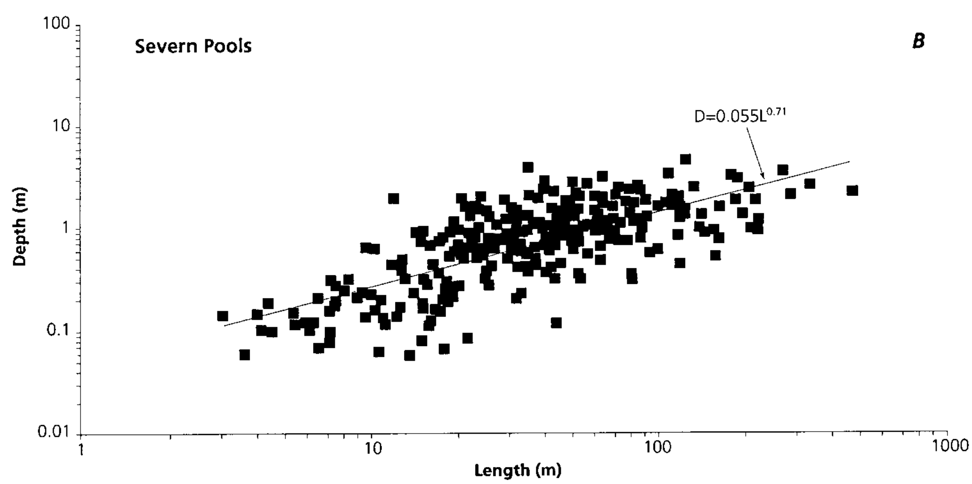


Figure 7. Relationship of (A) riffle height (H) to riffle length (L_r) and (B) pool depth (D) to pool length (L_p). Functions attributed to Flemming (1988) describe the average and maximum steepness (H/L) for fluvial dunes

Pool depth, length and asymmetry

Pools rarely exceeded 2 m in depth below the zero-crossing, and average 1 m in depth. Depths were only 1 or 2 per cent of the pool length. There was no significant difference in pool depths when comparing river reaches. Pool lengths were strongly positively skewed, with only a few pools being greater than 100 m in length.

Although many pools are asymmetric with longer proximal (upstream) sections (L_{p1}) compared to the length of the distal (downstream) sections (L_{p2}), the distributions for each reach are skewed with a tail of large L_{p1}/L_{p2} values. Within each reach the modal value tended to fall in the interval 0·3 to 0·5. This demonstrates that many pools are symmetrical ($L_1 = L_2$) or have proximal slopes shorter than the distal slopes. However, considering all data there is no relationship between pool asymmetry and the relative depth of pools to pool lengths (D/L_p) (Figure 5A).

The lack of preferred asymmetry means that there is no statistically significant difference in the distributions of proximal and distal angles (Snedecor's F-test). These angles are usually only a few degrees, generally less than 6° with a few extreme values up to 26° (Figure 6).

Pool depths are correlated positively with pool lengths (Figure 7B). Considering all the 285 data points:

$$D = 0 \cdot 055 L_p^{0 \cdot 71} \qquad r^2 = 0 \cdot 49 \tag{8}$$

or

$$D/L_p = 0 \cdot 055 L_p^{-0 \cdot 29} \tag{9}$$

The constant and exponent in Equation 8 are not significantly different from those in Equation 6 (95 per cent confidence limit). The similarity of the functions for both riffles and pools is as expected; in a zero-crossing analysis of a stationary series pools cannot be significantly deeper than riffles are high.

Relationship between riffle crest spacings and channel width

The mean channel width for each reach was obtained from survey data, whilst the average riffle to pool wavelength for each reach was derived by summing the mean length of riffles ($\bar{L}_r$) and pools ($\bar{L}_p$) within each reach. The results are given in Table II. The ratio of riffle–pool wavelength to channel width for the three reaches averages 3·01 despite a large variance in the data (Table I). This variance produced a characteristic broad spectrum of periodicities for each reach, with a number of harmonics at the medium to high end of the frequency spectrum. A particularly prominent peak occurs for each reach at a low frequency, of about 0·011 cycles per metre, representing a bed-level periodicity of about 90 m (Figure 4) equivalent to approximately $3\bar{W}$.

Relationship between riffle or pool length and channel width

The ratio of reach-average riffle or pool length to mean channel width (L_r/W and L_p/W) for reaches A, B and C was 1·31, 1·37 and 1·83 for riffles and 1·1, 1·43 and 2·04 for pools. The downstream increase in the

Table II. Average spacing of riffle crests

Reach	Width, W (m)	Wavelength, λ_p (m)	Ratio λ_p/W
A	36·11	90·41	2·50
B	30·75	85·43	2·78
C	43·58	163·71	3·76
Average ratio (λ_p/W) for whole reach			3·01

ratio reflects a downstream reduction in the channel gradient (cf. Yalin, 1977). Concomitantly, reach-average data for riffle and pool length increase in a downstream direction. Riffles and pools become flatter or shallower respectively with reduced overall slope angles but L_{r1} and L_{p1} increase disproportionately such that long-sections become increasing asymmetric.

Relationship between riffle height and water depth

For each reach, mean riffle height shows a scale-related increase in proportion to the bankfull depth (h). Reach A and B riffles scale with water depth approximately as $H/h = 0{\cdot}151$ and $0{\cdot}223$ respectively, whilst for reach C $H/h = 0{\cdot}201$. These results are remarkably similar to the scaling relationship common to fluvial dunes (Yalin, 1992; Allen, 1984, p. 333). It is evident that as bankfull water depth increases so does the average riffle height.

Relationship between riffle length and water depth

Reach-average riffle lengths increase with bankfull depths. The average L_r/h ratios for the Severn riffles in the three reaches are 7, 12 and 18. This result is comparable to scaling rules for dunes. For equilibrium dunes of length L_d, Yalin (1977, 1992) showed theoretically that $L_d = 2\pi\ h$. Yalin's analysis is supported by a compilation of field data wherein L_d/h is typically 5 to 7 and rarely exceeds 18 (Allen, 1984, p. 331). If the equilibrium length of a riffle–pool unit is defined as $L_\lambda = L_r + L_p$ then reach-average values of L_λ/h (i.e. 13·7, 25·0, 36·4) are approximately simple integer multiples of the term 2π (see Discussion).

DISCUSSION

The zero-crossing analysis may be criticized as it arbitrarily identifies any positive deviation as a 'riffle' regardless of the amplitude of the feature, its stratigraphy or its effect on river hydraulics. This problem could be prevented if 'tolerance' criteria (O'Neill and Abrahams, 1984) could be identified objectively. In addition, using the zero-crossing method the lower slopes of riffles might constitute part of the bathymetry of neighbouring pools, although sedimentologically and stratigraphically the distinction between riffle and pool sediments might be clear. Perhaps more important is the question of selection of an appropriate reach length, spatial sampling interval, and identification and removal of low-frequency signals. In this study we selected the longest possible records (*c.* 10 km) and (given that the sampling interval can effect the uniqueness of the data series) digitized at the smallest possible interval (10 m) to maximize the information content. Lag-free low-pass filters were justified in-as-much as they readily removed low-frequency signals producing mean stationary series. The optimal autoregressive (AR) models provide tests of the persistence of distinct spectral frequencies. In this manner, and in the absence of site-specific information, the methods of spectral analysis and zero-crossing analysis thus provide an objective, robust definition of riffles and pools. In this particular instance, results are in accord with the theory of Yalin (1971), in-as-much as pools in the Severn, *on average*, are spaced at intervals of $3W$. However, the largely continuous nature of spectra (i.e. Figure 4B; see also Richards, 1976) is salutary and demonstrates the essentially continuous spatio-temporal adjustment of bed elevation in alluvial rivers. Broad spectra of bedform wavelengths, albeit developed around defined central tendencies, seem characteristic of many rivers of different scale and have been known to exist for some time (Melton, 1962) but remain little remarked. Jain and Kennedy (1974) argue that such 'variance cascades' are the consistent bed-response, not only in time-varying flows, but also in sustained equilibrium flow conditions.

Reach-average data show that riffle and pool morphology is a function of stream gradient. On average, both pools and riffles become longer and increasingly asymmetric with reduced vertical expression as channel slope decreases. Riffles shorten and increase in height in deeper flows such that $H{:}L_r$ approaches a limit of 0·1. (Figure 7A). Equations 6 and 7 are consistent with well-established functions for the height–length relationship of fluvial dunes. The heights of most depth-limited riffles are lower for a given length when compared with equilibrium dunes but otherwise increase in a comparable fashion (Figure 7A)

It may be concluded that the steepest River Severn riffles have developed steepness values comparable to dunes. Of course, the comparison should not be unduly stressed, as other aspects of morphology such as

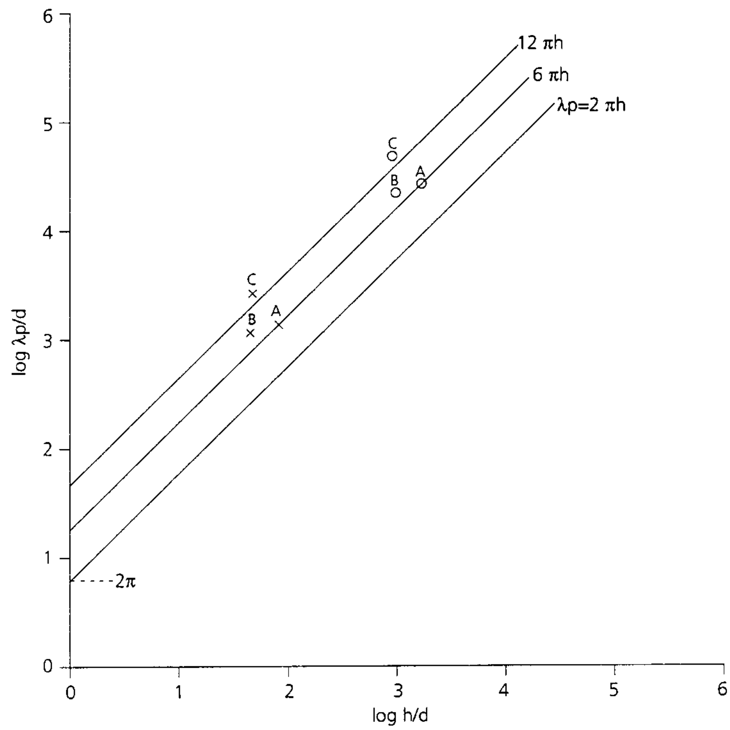


Figure 8. The spacing of riffle crests (λ_r) in reaches A, B and C in relation to bankfull water depth (h) and Yalin's curves of constant $\lambda_r = \alpha\pi h$ defined as a function of λ_r/d versus h/d. The range of bed grain size (d) in the River Severn is represented by assuming d = 0·075 m (×) or d = 0·004 m (○)

asymmetry are dissimilar, and the similarity of statistical regression functions (Figure 7A) does not necessarily imply similar process.

Nevertheless, Yalin (1977, 1992) proposed that a variety of 'granular bed material waves', although having different physical origins, may develop similar forms through bedload transport. Thus form is a response to a universal hydrodynamic scaling relationship (Yalin, 1977). Reach-average riffle–pool sequences in the River Severn tend towards the equilibrium periodic behaviour proposed by Yalin (1977, 1992), being described in all cases by a function of the form,

$$\lambda_p = \alpha 2\pi h \tag{10}$$

where α (c. 1 to 6), a simple integer multiple of π, increases as water depth decreases. Yalin's (1977) analysis was developed for near-equilibrium bedforms such that α ranges between 1 and about 3. Clearly riffle–pool structures where $\alpha > 3$ are long, low, depth-limited bedforms (Figure 8).

The question of the specific hydrodynamic control on riffle crest spacing remains illusive. In particular the eddy length scale (L_1) and the turbulent burst frequency (T_b) of large-scale flow structures associated with the riffle–pool unit are unknown. Equating Equations 5 and 10 Yalin (1977, 1992) obtained:

$$2\pi L_l \cong \lambda_p \tag{11}$$

Given an average value of L_λ of 88 m for reaches A and B, an eddy length of *c*. 14 m is obtained from Equation 11 for the Severn at bankfull.

Williams (1996) has shown that in most geophysical flows the frequency of large-scale coherent turbulent structures conforms to the general scaling relationship:

$$U_\infty T_b / L_l \equiv T^+ \cong 5 \text{ to } 6 \qquad (12)$$

where T_b is the time interval between these 'events' (in seconds), U_∞ is the free stream velocity and T^+ is the dimensionless 'event' frequency. Given measured bankfull depths (h) of 3·31 to 8·32 m, bankfull free-stream velocities (Carling, 1991) through pools and riffles varying between 0·69 and 1·635 m s^{-1} (averaging 1·47 m s^{-1}) and a value of L_l of 14 m, estimated values of T_b for bankfull conditions range from 50 to 100 s. These T_b values seem reasonable given directly measured values of $T_b \cong 8$ s and eddy length scales of a metre or two for in-bank flows in the study reaches (Heslop and Allen, 1989; Heslop *et al.*, 1994). The investigation of turbulence conducted by Heslop *et al.*, (1994) was not designed to identify very low-frequency coherent flow structure; nevertheless the peak linear frequency of turbulence ω_0 was derived for high flows and ranges between 0·1 and 0·3 (Heslop *et al.*, 1994). This is significant as $1/\omega_0 \cong h$ (Williams, 1996) in accord with the range of measured bankfull depths. Thus selection of bankfull depth as indicative of the mixing length is consistent with the values of $1/\omega_0$. Further work is planned to characterize scales of turbulent flow structure during bankfull flows.

The implication of convergent bedform steepness and broadly similar flow scaling parameters for riffle–pool units and for dunes has interesting implications with respect to spatial self-organization in geomorphological systems (see Hallet, 1990) and, in particular, for classifying bedforms genetically (Best, 1996). As a first approximation, an application of the principles of flow and bedload transport theory as applicable to coarse-grained dunes should apply equally to riffles. An appeal to 'special' processes such as the 'velocity-reversal hypothesis' (Keller, 1971) to explain riffle maintenance would have to be justified on alternative bases. The obvious difference is that riffles are of limited span such that river width varies between riffle and pool which results in large-scale flow separation in plan induced by the changes in river bank alignment. This separation alone has been cited to justify the velocity-reversal hypothesis (e.g. Teisseyre, 1983, 1984; Thompson *et al.*, 1996). However, Yalin (1977) and Nelson (1990) argue that the constraints of channel width on bedform geometry are of secondary significance compared with the attributes of longitudinal turbulent flow. It follows that attempts to demonstrate the functional control of plan-view flow separation on riffle–pool morphology need to demonstrate a universal application rather than a site-specific example.

CONCLUSIONS

The River Severn data provide detailed summary information on riffle and pool geometry. Despite variance, average riffle crest spacings equal three times the channel width. Riffle height (H) is a positive function of riffle length (L_r) and bankfull depth (h). Riffle length is a function of bankfull depth and riffle spacings may scale with coherent turbulent flow structures with an event frequency of the order of 50 to 100 s. The statistical relationships between H and L_r, and H and h are similar to those relating height, length and water depth for equilibrium dunes, and are consistent with the theoretical analyses of Yalin (1977). Thus reach-average empirical data consistently indicate agreement with theory. The variance, however, emphasizes the continuing dynamic adjustment of channel form to hydraulic forcing. Taken together, these results should prompt a reconsideration of the significance of identifying central tendencies within continuous broad spectra. For example, the considerable variance indicates that the morphology of individual riffle–pool units may be significantly different to that implied by average scaling functions designed to apply to the reach scale rather than at the scale at which the sediment transport process actually operates. These issues raise intriguing questions with respect to process response, dynamic similarity and bedform genetic classification.

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